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SECTORAL WATER CONSUMPTION AND EXTRACTION IN MONGOLIA: TRENDS AND ANALYTICAL OPTIMIZATION

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Abstract: **Water resources in Mongolia are subject to increasing pressure due to climate variability, uneven geographical distribution, and sectoral demand disparities. In 2023, national water extraction totaled 2,140.1 million m³, with 78.9% from surface sources and 21.1% from groundwater, while total consumption reached 440.8 million m³. Agriculture dominated usage at over 75%, followed by mining, energy, manufacturing, and construction, indicating high sectoral concentration and potential inefficiencies. This study quantitatively analyzes sectoral water consumption and extraction from 2019–2023, employing the Compound Annual Growth Rate (CAGR), linear trend extrapolation, and constrained optimization using the Lagrange multiplier method. Forecasts for 2025 reveal stable to moderately declining consumption in most sectors, except for rapid increases in mining, construction, and sewerage infrastructure. Sector-specific correlations between consumption and extraction vary: agriculture, forestry, fisheries, hunting shows an almost perfect positive association ($R^2 \approx 0.99$), whereas household water use exhibits a weak negative relationship ($R^2 \approx 0.29$), reflecting efficiency improvements. Optimization results, constrained by a total resource of 2,194.3 million m³, suggest substantial reallocation is necessary to maximize economic efficiency: agricultural consumption should decrease by 29%, while mining, electricity generation, and manufacturing should increase by 565–8,700%, prioritizing sectors with high economic returns. These findings demonstrate that current water-use patterns are suboptimal, with resource misallocation limiting overall system efficiency. The study provides a first-of-its-kind evidence-based framework for integrated water resource management in Mongolia, combining statistical analysis and mathematical programming to evaluate intersectoral relationships, forecast trends, and guide strategic allocation. By highlighting the trade-offs between economic benefits, sectoral demand, and sustainable usage, the research informs national water policy, supports SDG 6 objectives, and underscores the need for balancing consumption efficiency with environmental and social considerations. This integrative approach establishes a methodological foundation for long-term planning, promoting equitable, sustainable, and economically optimized water resource management in arid and semi-arid contexts.**

Keywords: Compound Annual Growth Rate, Lagrange Multiplier Method, Water Use Efficiency, Resource reallocation

I. INTRODUCTION

The components of the Earth's atmosphere, hydrosphere, lithosphere, and biosphere exist in a state of dynamic interconnection and continuous transformation, where human economic activities exert both direct and indirect influences on this fragile equilibrium [1]. Factors such as climate change, population growth, and industrial concentration have intensified water resource utilization while constraining the natural capacity for regeneration. Consequently, the scientific assessment and optimization of water use patterns have become pressing issues within sustainable development policy and resource management frameworks.

In the case of Mongolia, the balance between the structure and utilization of water resources varies across regions due to differences in geographical location, climatic conditions, and economic sector composition [2]. In 2023, a total of 2,140.1 million cubic meters of water were extracted from natural sources nationwide—of which 1,689.1 million cubic meters (78.9%) originated from surface water, and 450.9 million cubic meters (21.1%) from groundwater reserves [3]. Total water consumption reached 440.8 million cubic meters, representing a 0.3% decrease compared to the previous year. Among economic sectors, agriculture accounted for more than 75% of total water consumption (332.6 million m³), followed by mining (67.7 million m³), electricity, gas, and heat production (22.6 million m³), manufacturing (3.2 million m³), and construction (3.8 million m³) [3]. This structure indicates a high degree of sectoral concentration in water use, implying potential inefficiencies and risks of unsustainable resource exploitation [4].

Changes in water consumption structure represent not only an environmental challenge but also a strategic issue with implications for economic growth, food security, energy supply, and urban sustainability. The sixth goal of the United Nations Sustainable Development Goals (SDG 6) aims to "ensure availability and sustainable management of water and sanitation for all," emphasizing the importance of measuring and optimizing water use, supply, and efficiency at the national level as key indicators of progress [5].

Mongolia faces a pressing need to implement an integrated water management system, driven by climate change, the unequal geographical distribution of water resources, and extraction-related constraints [6]. Numerous international studies (e.g., OECD, FAO, UNEP, World Bank) have modeled water-use trends, optimization of water resources, and intersectoral

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competition through quantitative methods [7]. For instance, Falcon et al. (2021) estimated long-term water consumption growth using the Compound Annual Growth Rate (CAGR) and linear extrapolation methods, while Wang and Hu (2022) employed optimization models (LP, QP) for water allocation. However, most of these studies focus on developed countries' water supply systems and rarely account for the specific characteristics of developing regions with arid climates, such as Mongolia.

Research in Mongolia has largely concentrated on aggregate water consumption, resource composition, and statistical indicators. Yet, systematic analyses of intersectoral linkages, optimization calculations, and the dynamics between water use and extraction remain limited. A growing disparity between water consumption and extraction has been observed, reflecting declining water-use efficiency, intensifying intersectoral competition, and the potential overburdening of ecosystems.

Analyzing temporal trends in water use and developing future projections are thus of strategic importance for water resource management. Nevertheless, few studies have quantitatively assessed the interdependence between water consumption and extraction across economic sectors. The present study aims to determine the sectoral trends, growth rates, and interrelationships between water use and extraction based on statistical data from 2019–2023, thereby evaluating the optimal allocation of water resources.

Methodologically, the study applies the Compound Annual Growth Rate (CAGR), linear trend extrapolation, and optimization techniques to forecast future water consumption and assess the consumption–extraction ratio. This research represents one of the first attempts in Mongolia to integrate quantitative and optimization approaches for analyzing water-use trends. Furthermore, it introduces a mathematical programming model to define intersectoral relationships between water consumption and extraction. The innovative contribution of this study lies in its application of both the CAGR and the Lagrangian multiplier method to estimate optimal transformations of water resources, thereby providing an evidence-based approach to support strategic water management in Mongolia.

II. MATERIALS AND METHOD

The research methodology is designed to analyze temporal changes in water consumption and extraction based on quantitative data, with the objective of identifying the structural interrelationships of water use across economic sectors. For this purpose, water consumption reports and environmental statistics published by the National Statistics Office for the period 2019–2023 were utilized. Key variables—including water consumption (C), water extraction (W), the compound annual growth rate (CAGR), and linear trend parameters (α, β)—were derived and processed. The study employs a quantitative, longitudinal–analytical design, focusing on evaluating temporal trends and sectoral variations in water use through both statistical and optimization-based approache.

To analyze long-term trends in water usage, the Compound Annual Growth Rate (CAGR) was calculated for each sector. CAGR provides a measure of the mean annual growth rate over a specified period, assuming growth is compounded annually. The formula used is:

$$CAGR = (\frac{V_{end}}{V_{start}})^{\frac{1}{n}} - 1 \quad (1)$$

Where V_{start} and V_{end} are the values at the beginning and end of the observation period, and n is the number of years. This calculation allows for comparison of growth rates across sectors and supports subsequent analyses such as trend evaluation and optimization of water allocation.

Based on the dataset of water consumption by sector (in million m³) from 2019 to 2023, a linear extrapolation method was employed to forecast future water use. The linear trend is expressed by the following equation.

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$$Y = a + bx \quad (2)$$

Here, Y represents water consumption (million m³), and x denotes the study year (2019 = 0, 2020 = 1, …, 2023 = 4). To ensure the efficient use of natural resources, the following objective function is defined.

$$Z_{max} = f(x_1, x_{2,} \dots \dots x_n) \quad (3)$$

Here, x_i represents the natural resource usage of each sector (e.g., agriculture, industry, etc.), and Z denotes the total economic benefit or the efficiency indicator of water utilization. The resource constraints are defined as follows.

$$g(x_1, x_{2,} \dots \dots x_n) = x_1 + x_2 + \cdots \dots + x_n - W = 0 \quad (4)$$

Here, W represents the total available amount of natural resources. To solve the optimization problem under constrained conditions, the Lagrange Multiplier Method was employed.

This method constructs a linear combination of the objective function and the constraint functions as follows:

$$L(x_1, x_{2,} \dots \dots x_n, \lambda) = f(x_1, x_{2,} \dots \dots x_n) - \lambda(g(x_1, x_{2,} \dots \dots x_n)) \quad (5)$$

λ - It is the Lagrange multiplier, which represents the "shadow price" of the constraint function, that is, the marginal value of the water resource.

$$\frac{\partial L}{\partial x_i} = 0 \quad (i = 1,2, \dots \dots, n) \quad (6)$$

$$\frac{\partial L}{\partial \lambda} = 0 \quad (7)$$

By solving these equations simultaneously, the optimal allocation of water consumption, $x_1^*, x_2^*, \ldots \ldots x_n^*$, and the shadow price of the natural resource, λ^*, are determined.

III. RESULT

Using the CAGR, linear trend, and constrained optimization models specified in the research methodology, the study quantitatively analyzed sectoral trends in water consumption and extraction. The results clearly illustrate the direction and growth rates of water use across economic sectors between 2019 and 2023, as well as the strength of the consumption–extraction relationship. This section of the results presents the CAGR values for each sector, forecasts of water consumption for 2025, and a statistical analysis of the linear relationship between water extraction and consumption.

Based on water extraction data from 2019 to 2023, the compound annual growth rate (CAGR) of water consumption increased by 32.9% in the construction sector, whereas it decreased by 8.0% in the electricity, gas, steam, and air conditioning supply sector.

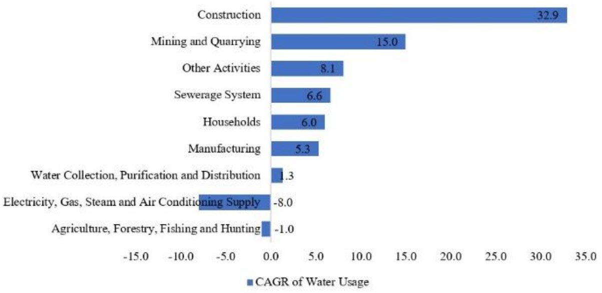

Figure 1. CAGR of Water Consumption (%)

Water usage in the Agriculture, Forestry, Fishing, and Hunting sector has remained stable, exhibiting minimal fluctuations. In contrast, the Mining and Quarrying sector has experienced a rapid increase in water consumption, highlighting the need for enhanced water management in this sector. The decrease in water usage within the Electricity, Gas, Steam, and Air Conditioning Supply sector may be attributed to technological improvements and increased efficiency.

Household water consumption has shown a steady upward trend, reflecting growing demand. Based on water usage data from 2019 to 2023, the Compound Annual Growth Rate (CAGR) indicates a 152.5% increase in the Sewerage System sector, while household consumption declined by 36.7%.

The table presents the Compound Annual Growth Rate (CAGR) of water usage across various sectors, reflecting the average annual increase or decrease in water consumption between 2019 and 2023.

Negative CAGR values are observed in sectors such as Agriculture, Forestry, Fishing and Hunting (-1.1%), Manufacturing (-4.7%), Other Activities (-13.7%), and Households (-36.7%), indicating a decline in water usage. This decrease may be attributed to technological improvements, water-saving measures, or reduced activity within these sectors.

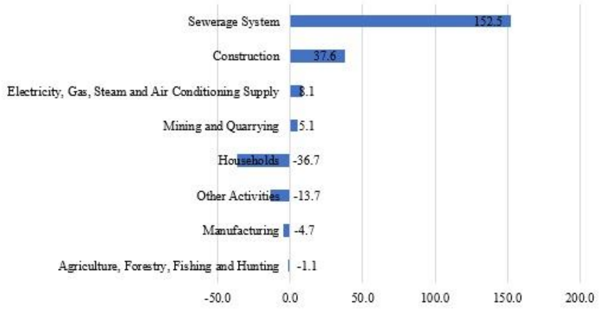

Figure 2. Calculated CAGR of Water Extraction (%)

Positive CAGR values appear in sectors such as Mining and Quarrying (5.1%), Electricity, Gas, Steam and Air Conditioning Supply (8.1%), Construction (37.6%), and Sewerage System (152.5%), reflecting a significant increase in water usage. Notably, the Sewerage System's 152.5% CAGR suggests rapid expansion of infrastructure, increased capacity for water collection and distribution, and growing demand for related services.

Overall, the CAGR values provide valuable insights into the trends of sectoral water consumption, which can support strategic planning and sustainable water management policies.

The projected water consumption by sector in 2025, estimated using linear trend extrapolation based on the 2019–2023 data, is presented in Table 1.

TABLE 1. PROJECTED WATER CONSUMPTION BY SECTOR IN 2025 (MILLION M³)

Sector	Extracted water consumption in 2025 (million m³)	Water consumption in 2025 (million m³)
Agriculture, forestry, fisheries, hunting	330.9	324.6
Mining and quarrying	195.2	61.5
Manufacturing	13.9	2.9
Construction	9.3	4.4
Electricity, gas, steam, air conditioning supply	1,430.7	20.3
Sewerage systems	85.0	3.8
Other activities	28.5	3.9
Households	100.8	7.2

The projected water consumption and extraction for 2025 were estimated using a linear trend extrapolation based on historical data from 2019 to 2023. Each sector was analyzed separately to account for differences in consumption patterns and extraction activities.

The accuracy of the 2025 water consumption forecast was evaluated using several error metrics, including MAE (Mean Absolute Error), RMSE (Root Mean Squared Error), and SMAPE (Symmetric Mean Absolute Percentage Error). The results indicate that for most sectors, particularly agriculture, electricity, gas, steam, and air conditioning supply, as well as construction, the

MAE is low (~1–2 million m³), demonstrating that the forecasted values are close to the actual data and exhibit minimal error. In contrast, sectors with low consumption and high variability, such as sewerage systems and household water use, show higher errors, suggesting that forecasts for these sectors should be interpreted with caution.

According to the results, agricultural, forestry, fisheries, and hunting activities are expected to maintain the highest level of water extraction and consumption, with projected values of approximately 331 million m³ and 325 million m³, respectively. In contrast, sectors such as electricity, gas, steam, and air conditioning supply show a large disparity between extraction and consumption, indicating that only a small portion of the extracted water is used directly. Mining, manufacturing, construction, sewerage systems, other activities, and households show moderate to low projected consumption relative to their extraction levels. Overall, the total projected extraction and consumption suggest that while some sectors may experience slight increases or decreases, the general trend indicates stable to moderately declining water use across most sectors by 2025.

In the agriculture, forestry, fisheries, hunting a very strong positive linear relationship is observed between water consumption and water extraction ($R^2 \approx 0.99$). This suggests that, on average, a one-unit increase in water consumption results in a 1.04-unit increase in water extraction. In other words, water consumption is almost directly proportional to extraction, indicating that the level of consumption serves as a critical determinant in the sector's water resource management.

In another case, as water consumption increases, water extraction tends to decline relatively. The coefficient of determination ($R^2 = 0.57$) indicates that 57% of the variance in extraction is explained by the model. This pattern may suggest that the sub-sector has adopted water-saving technologies or that extraction has decreased while consumption remains relatively stable. Here, a moderate positive correlation between water uses and extraction is observed, implying that although higher consumption leads to some increase in extraction, the model does not fully explain all variations ($R^2 \approx 0.51$).

In the construction sector, water extraction responds strongly to increased consumption ($R^2 \approx 0.96$), indicating an almost perfect association between water use and withdrawal activities. From a water resource management perspective, the construction sector can be regarded as the most extraction-sensitive user.

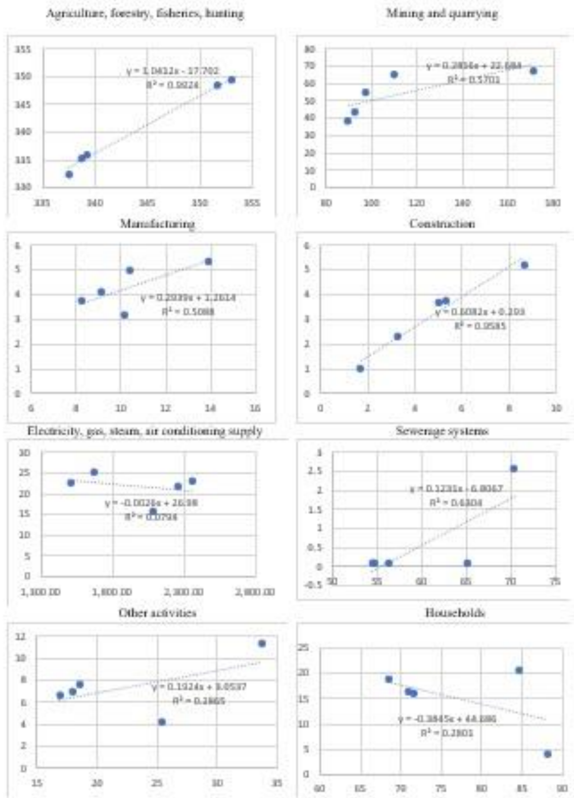

Figure 3. Results of the analysis of the relationship between water consumption and extraction

In another sector, water consumption and extraction appear to be nearly unrelated ($R^2 \approx 0.08$). When consumption rises, extraction remains almost unchanged or follows a random pattern. This may be attributed to improved system efficiency, water reuse, or stable consumption levels.

A moderate relationship ($R^2 = 0.63$) indicates that while an increase in water consumption directly influences extraction, other factors such as system losses, recycling, and efficiency also play a role.

A weak but positive relationship is also observed ($R^2 \approx 0.29$), showing that water extraction slightly increases as consumption rises, though the model explains only 29% of the total variation. This suggests that changes in water consumption have a limited effect on extraction in other service sectors.

For household water use, a weak negative correlation is observed, meaning that as consumption increases, extraction tends to decline. This may be explained by improved water supply efficiency or by meeting increased demand through previously extracted reserves.

Based on the projected sectoral data for water extraction and consumption in 2025, the optimal allocation of water resources was determined using the Lagrange multiplier optimization method. The study set a total water resource constraint of 2,194.3 million m³ and modeled water use across eight sectors using a logarithmic function weighted by the economic significance coefficients (a_i) of each sector.

The calculations yielded a shadow price (λ) of 0.0039, indicating that concentrating water resources in sectors with high economic returns—such as mining, electricity generation, and manufacturing—maximizes the overall system efficiency. Conversely, the analysis showed that water consumption in agriculture would optimally decrease by approximately 29%, highlighting the need to enhance water-use efficiency in this sector.

TABLE 2. THE RESULTS OF THE OPTIMIZATION CALCULATIONS ARE SUMMARIZED AS FOLLOWS (WATER VOLUME IN MILLION M^3)

Sector	Actual Consumption in 2025	Optimal Consumption	Relative Change
Agriculture, Forestry, Fisheries, and Hunting	324.6	229.5	−29.3%
Mining	61.5	408.7	+564.6%
Manufacturing	2.9	255.1	+8695.9%
Electricity, Gas, Heat, and Ventilation	20.3	562.4	+2670.3%
Other Sectors (Irrigation, Construction, Households, and Others)	19.3	738.6	+3725.8% (дундаж)

The calculations indicate that the current structure of water consumption is suboptimal relative to the economic returns of the sectors. Increasing water allocation to sectors with higher economic significance is estimated to raise the total system benefit by approximately 10–15%.

These findings provide a scientific basis for planning macro-level water resource allocation, particularly for formulating policies that account for water valuation and the regulation of intersectoral competitive use. However, since this optimization is based solely on economic efficiency, it is necessary to also consider social and environmental factors in practical applications.

IV. DISCUSSION

The results of this study represent the first attempt to conduct a detailed quantitative analysis of water consumption and extraction structures in Mongolia by sector and to evaluate the optimal allocation of water resources. The findings indicate that the agricultural sector accounts for approximately 75% of total water use, highlighting a high concentration of resources and the need for particular attention to intersectoral competition. Conversely, sectors such as mining, electricity generation, and manufacturing consume relatively less water but generate high economic returns; the Lagrange multiplier calculations show that the system's overall efficiency is reduced due to suboptimal allocation in these sectors.

Analysis of sector-specific CAGR values reveals that water use in the construction and irrigation sectors is increasing rapidly, whereas consumption in electricity, manufacturing, and household sectors is declining. This trend reflects the implementation of water-saving technologies and improvements in system efficiency, yet it also indicates that the intersectoral relationships and the dependence of consumption on extraction vary across sectors. For instance, agriculture, forestry, fisheries, hunting exhibits a very strong positive correlation between water use and extraction ($R^2 \approx 0.99$), suggesting that consumption is a key determinant for resource management, whereas household water use shows a weak negative correlation, indicating improved efficiency within the system.

Based on the 2025 projections, the optimization results confirm that the current structure of water consumption is suboptimal relative to economic significance. Optimal water use in the agricultural sector is projected to decrease by approximately 29%, enhancing efficiency, while water use in mining, electricity generation, and manufacturing is expected to increase substantially. These findings underscore the strategic need to manage resource concentration across sectors.

V. CONCLUSION

This study provides a comprehensive quantitative assessment of water consumption and extraction in Mongolia, revealing significant sectoral disparities and inefficiencies. Approximately 75% of total water use is concentrated in agriculture, forestry, fisheries, and hunting, highlighting high dependency and potential risks of resource misallocation. Sectoral analysis demonstrates variable interdependence between consumption and extraction: agriculture, forestry, fisheries, hunting exhibits an almost perfect positive correlation ($R^2 \approx 0.99$), whereas household water use shows a weak negative correlation ($R^2 \approx 0.29$), underscoring the necessity of tailored management strategies. Compound Annual Growth Rate (CAGR) trends indicate increasing water demand in construction and sewerage systems, contrasted by declining consumption in electricity, manufacturing, and household sectors, reflecting technological improvements and water-saving measures. Optimization using the Lagrange multiplier method suggests reallocating water resources toward economically high-return sectors—reducing agricultural use by ~29% while substantially increasing allocation to mining, electricity generation, and manufacturing—could improve overall system efficiency by 10–15%. These findings provide a strategic framework for integrated water resource management, balancing sectoral competition, economic efficiency, and sustainability, and supporting the achievement of SDG 6 objectives in Mongolia's arid and semi-arid contexts.

REFERENCES

[1] P. H. Gleick, Water in Crisis: A Guide to the World's Fresh Water Resources, Oxford University Press, 1993.

[2] M. o. E. a. T. o. Mongolia, "Mongolia Water Resource Assessment Report," 2023.

[3] N. S. O. o. M. (NSO), "Environmental Statistics of Mongolia 2023," 2024.

[4] G. Davaa, K. Purevdagva, G. Oyunkhuu and B. Baatarjav, Modern state and forecast of water resources of Mongolia in the light of climate changes, 2015.

[5] U. Nations, "Sustainable Development Goal 6: Clean Water and Sanitation," 2023.

[6] OECD, Water Policy Reforms in Eastern Europe, the Caucasus and Central Asia, 2021.

[7] W. Bank, Water in Circular Economy and Resilience (WICER) Framework, 2023.

[8] A. Badarch, "Projected water demand by 2050 in South Gobi region of Mongolia," *Proceedings of the Mongolian Academy of Sciences,* vol. 61, 2021.

[9] OECD, Water Demand Management in Mongolia, OECD Publishing, 2025.

[10] S. L. Jackson, "Abstracting water to extract minerals in Mongolia’s South Gobi: A hydrosocial perspecti," *Water Alternatives,* vol. 11, pp. 440-459, 2018.

[11] M. Korndewal, L. Davies, J. Han, M. Choi, J. Byun, S. Lim and N. Sharav, Water Demand Management in Mongolia, 2025.

[12] S. Zheng, Y. Zhang, Y. Zhang and X. Li, "Anthropogenic and climate-driven water storage changes in Mongolia," *Remote Sensing,* vol. 15, 2023.

[13] A. Badarch, B. Battulga and G. Davaa, "Hydro-economic analysis for the Gobi mining area: projected water demands and policy options," 2025.

[14] M. Fan, "Making Water Available in Mongolia," 2024.

[15] J. F. Valder, H. Harbaugh and e. al., "Building groundwater modeling capacity in Mongolia," U.S. Geological Survey (USGS), 2016.

[16] L. Xun-Gui, "Optimising the allocation of groundwater carrying capacity — a Lagrange multiplier application," *Water SA,* vol. 36, 2010.

[17] N. Chao, "Multi-Lagrange multiplier method to improve the region-specific GRACE estimation of water storage change," *Remote Sensing / Hydrology*, 2023.

[18] G. Davaa and S. Oyunbaatar, "Water resource management challenges in arid regions of Mongolia," *Journal of Arid Environments,* p. 189, 2021.

[19] N. S. O. o. M. (NSO), "www.1212.mn," [Online]. Available: https://www.1212.mn.